Broadband Optical Delay with Large Dynamic Range Using Atomic Dispersion

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Abstract. We report on a tunable all-optical delay line for pulses with optical frequency within the Rb D_2 absorption line. Using frequency tuning between absorption components from different isotopes, pulses of 10 ns duration are delayed in a 10 cm hot vapour cell by up to 40 ns while the transmission remains above 10%. The use of two isotopes allows the delay to be increased or decreased by optical pumping with a second laser, producing rapid tuning over a range of more than 40% of the initial delay at 110°C. We investigate the frequency and intensity ranges in which this delay line can be realised. Our observations are in good agreement with a numerical model of the system.

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'Slow light' refers to the propagation of a pulse of light in a dispersive medium at a group velocity much less than c [1]. By its use, optically encoded information can be controllably delayed without the need for electronic transduction. This is of great interest for telecommunications, where there is a need for tunable all-optical delay lines for high-speed optical signal processing, e.g., buffering optical data packets [2]. Additionally, such a system may be included in the growing repertoire of tools available for quantum information processing.

To minimise pulse distortion, an optical delay line should have approximately constant positive dispersion in a spectral region $\Delta\nu$ of width larger than the inverse of the pulse duration, i.e., $\Delta\nu > 1/\tau$. The transmission should be high and the fractional delay (the ratio of the delay δ to the pulse duration), which provides a practical metric, should exceed unity, i.e., $\delta/\tau > 1$.

Narrow spectral features in the refractive index of atomic media due to light-induced ground-state coherence can result in sub and superluminal pulse propagation [3] and even 'light storage' [4, 5]. Using atomic media to produce optical delay has predominantly exploited the steep dispersion associated with electromagnetically induced transparency (EIT) [6, 7, 8]. While EIT in atomic vapour can produce extremely low group velocities it has a severe bandwidth limitation owing to the narrow spectral range over which the transparency and steep dispersion occurs, making $\delta/\tau > 0.3$ difficult to obtain. Because of this, it has been suggested that ultracold atomic samples may be required to achieve large fractional delays in EIT-based delay lines [9].

In solid-state media, attempts to obtain larger bandwidth include methods based on spectral hole burning [10] and the use of gain features such as stimulated Brillouin scattering [11] and Raman amplification [12] in optical fibres.

An attractive approach to realising a wide-bandwidth delay line utilises the intrinsic positive dispersion and high transmission between two absorption lines in an atomic vapour. This has allowed, Camacho *et al.* to observe large fractional delays for light pulses tuned between the ^{85}Rb hyperfine components of the D_2 line [13]. In addition, this technique provides a high degree of spatial homogeneity in both dispersion and absorption, allowing the delay of transversely encoded optical information (images) [14].

In this paper, we investigate the delay and transmission properties of optical pulses tuned within the Rb D_2 line in a heated vapour with natural isotopic abundance. Moreover, we modify the dispersion by optical pumping to either reduce or enhance the number of interacting atoms on one of the absorption components, allowing rapid control of the delay.

The scheme of our experimental setup is shown in figure 1a. Signal and optical pumping radiation is produced using extended cavity diode lasers tuned to the rubidium D_2 (figure 1b) and D_1 lines, respectively. The laser frequencies are controlled with reference to Doppler-free saturation spectroscopy performed in auxiliary Rb cells and the spectral purities are analysed using Fabry-Perot cavities.

Optical pulses of 9.3 ns duration (FWHM) with a repetition rate of 10 MHz are generated from the cw signal laser using an electro-optic modulator (EOM) triggered

by a waveform generator (figure 1a). The optical intensity is controlled by a neutral density filter (ND) before propagation through a 10 cm vapour cell heated in a thermally insulated oven. The transmitted pulses are detected using a fast photodiode and recorded on an oscilloscope.

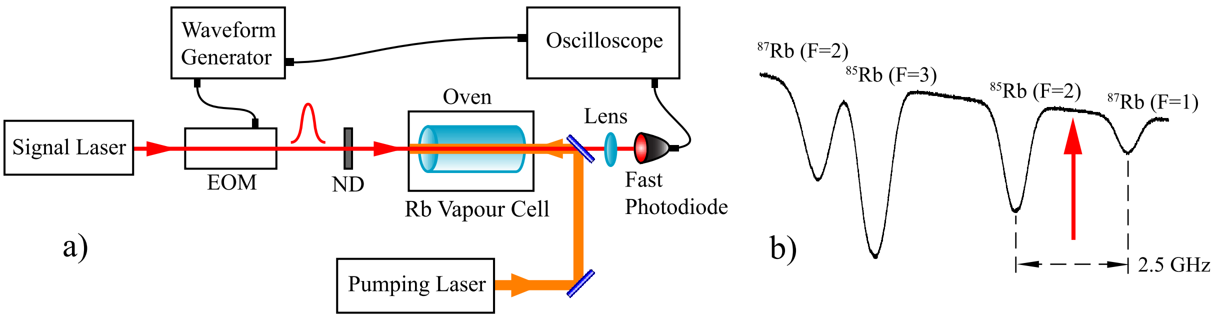

Figure 1. (Colour Online) a) Schematic of the experimental setup. The optical pumping laser is used only for delay tuning. b) Rb D_2 line absorption spectrum at room temperature where the arrow indicates the region of the signal laser frequency used.

For rapid tuning of the delay, optical pumping radiation at either the ^{87}Rb (F=1) or (F=2) component of the D_1 line is applied, approximately counter-propagating to the signal beam. A lens minimises spatial deviation of the signal beam induced by optical pumping.

The signal laser frequency is tuned to the D_2 line at $\lambda = 780$ nm between the ^{85}Rb (F=2) and ^{87}Rb (F=1) components, which have a separation of $\sim$2.5 GHz (figure 1b). The inherent positive dispersion and low absorption in this broad spectral region allows large fractional delays with high transmission. In figure 2a the observed optical delays for pulses at the frequency of peak transmission are shown relative to a non-interacting reference pulse for temperatures between 105°C and 135°C. A fractional delay $\delta/\tau = 4.3$ was observed for a transmission of 9% with good pulse shape preservation, where the pulse duration narrowed by less than 10%. It should be noted that the fractional delay is limited in these experiments by the pulse duration we are able to generate. The observed delay and transmission are plotted against temperature in figure 2b, along with our numerical predictions.

For our numerical predictions, we model the absorption coefficient $\alpha(\omega)$ and the real part of the refractive index $n(\omega)$ of the Rb D_2 line using a convolution of profiles arising from homogeneous and inhomogeneous broadening mechanisms. The homogeneous profile includes contributions from natural broadening, collisional broadening [15] and power broadening and is convolved with the thermal Gaussian Doppler profile. The group velocity is then approximated using the first derivative of $n(\omega)$ with respect to ω,

$$v_g = \frac{c}{n(\omega_0) + \omega_0 \frac{\partial n(\omega)}{\partial \omega}} = \frac{\partial \omega}{\partial k}. \tag{1}$$

At the frequency of peak transmission between the two absorption lines, the

probability for resonant interaction via the Doppler shift is small, even at the temperatures used in these experiments. Instead, interaction occurs mainly through the broad wings of the homogeneous component of the profile. For example, at $T = 110°$C the probability of an atom belonging to a velocity class with a detuning of 1 GHz from resonance and an optical bandwidth of 110 MHz (appropriate for our pulse duration) is about 10^{-4}. Using an estimated number density of 10^{13} cm^{-3} (based on Ref. [16] and taking into account the natural isotopic ratio), the optical depth αL is 0.4 for a 10 cm cell.

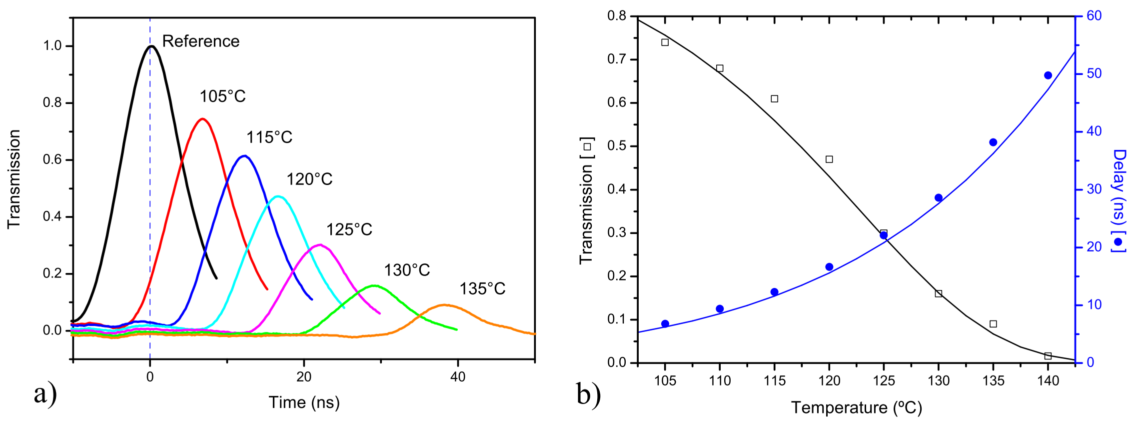

Figure 2. (Colour Online) a) Delayed pulses with increasing temperature. The transmission is normalised to a non-interacting reference pulse. b) Observed transmission (□) and delay (●) with numerical predictions (curves).

Our pulse bandwidth of 110 MHz is less than the width of the transmission window of approximately 1 GHz which allows the variation in $v_g(\omega)$ and $\alpha(\omega)$ between the absorption components to be explored. The frequency dependence of the pulse delay and transmission at different temperatures is shown in figure 3. For 10% transmission, suggested in Ref. [13] as a practical limit for a delay line, the usable bandwidth decreases from 1.1 GHz at 110°C to 540 MHz at 127°C. At the former temperature we expect that a fractional delay an order of magnitude larger could be achieved with shorter pulses that utilise the available bandwidth.

The effect of saturation is quantified in our numerical model by the saturation parameter $S = I/I_{sat}(\omega)$, where $I_{sat}(\omega)$ is the saturation intensity which is inversely proportional to the frequency dependent absorption cross section. This means saturation has little effect on the wings of a homogeneously broadened line. In contrast, for an inhomogeneously broadened line, saturation can occur over the entire profile. This means that although increasing the temperature decreases the usable bandwidth due to Doppler broadening (figure 3), at a given temperature the bandwidth may be increased by increasing the saturation.

Expression (1) for v_g provides an accurate approximation for the delay at frequencies near the point of peak transmission. However, the agreement is found to reduce for frequencies closer to the absorption peaks. This may be due to higher spectral derivatives

in $n(\omega)$ becoming more significant. It was observed that the pulse shape suffers little distortion from dispersive and absorptive mechanisms and remains preserved. This supports the finding in Ref. [13] that these mechanisms compensate one another.

Temperature tuning provides a method for changing the delay over a wide range, but the change is inherently slow as the cell heats or cools. Fast control of the delay was achieved in Ref. [17] by using two additional laser fields to modify the dispersion by saturating both absorption lines to reduce the atomic ground state population. While this approach gives rapid delay tunability, it produces a relatively small tuning range. In the present work, where the pulses are tuned between absorption resonances from different isotopes, hyperfine optical pumping allows the ground state population of one of the resonances to be strongly modified with minimal modification of the other. An optical pumping laser tuned to one of the ^{87}Rb components of the D_1 line is used to modify the population of ^{87}Rb (F=1) ground state atoms interacting with the signal. Tuning the optical pumping laser to the D_1 ^{87}Rb (F=1) or (F=2) component respectively reduces or increases the population in the F=1 ground state (figure 4b and c). Pumping on the D_1 line is more efficient than on the D_2 line as it has no cycling transition. Moreover, the optical depth is less both for this line and for the ^{87}Rb component, giving greater longitudinal pumping homogeneity. In this manner, at 110°C the delay was reduced by approximately 17.5% or increased by 25% of the unmodified delay

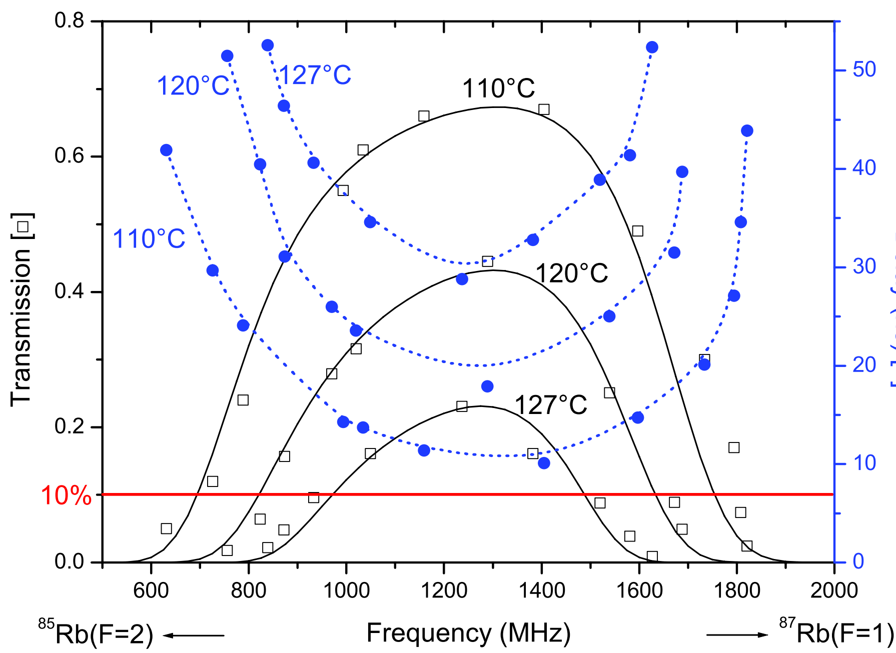

Figure 3. (Colour Online) a) Frequency dependence of the pulse delay and transmission for a range of temperatures. The frequency is measured from the absorption peak of the ^{85}Rb (F=2) component. The points are experimental observations and the solid curves are our numerical predictions for transmission. The saturation parameter $S = 20$, 8 and 4 for $T = 127$, 120 and 110°C, respectively. Interpolations (dashed) are included as a guide to the eye for the delay.

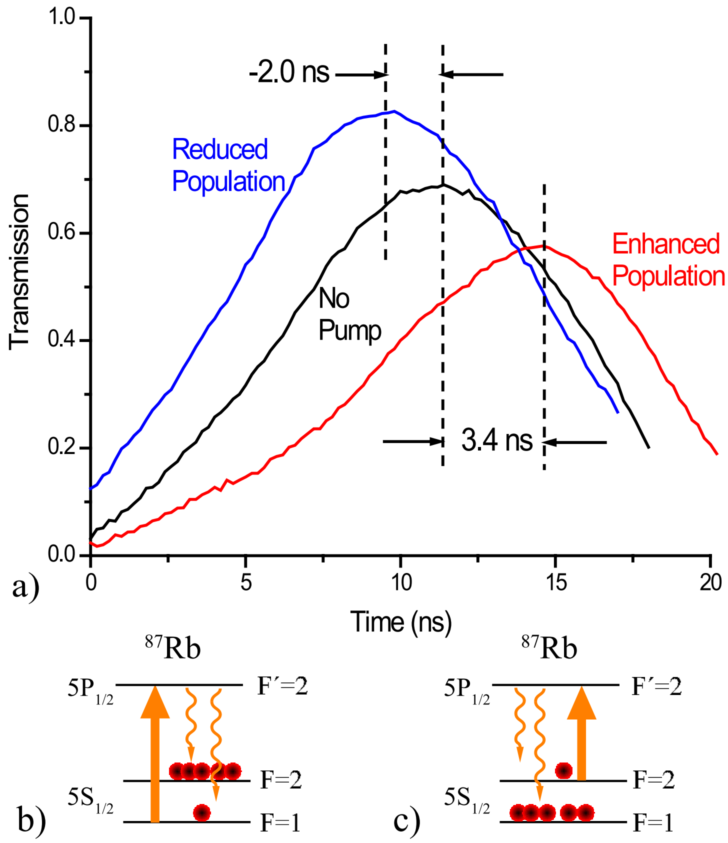

Figure 4. (Colour Online) a) Reduced and increased delay via optical pumping, which reduces b) or enhances c) the population of the ^{87}Rb (F=1) ground state, respectively.

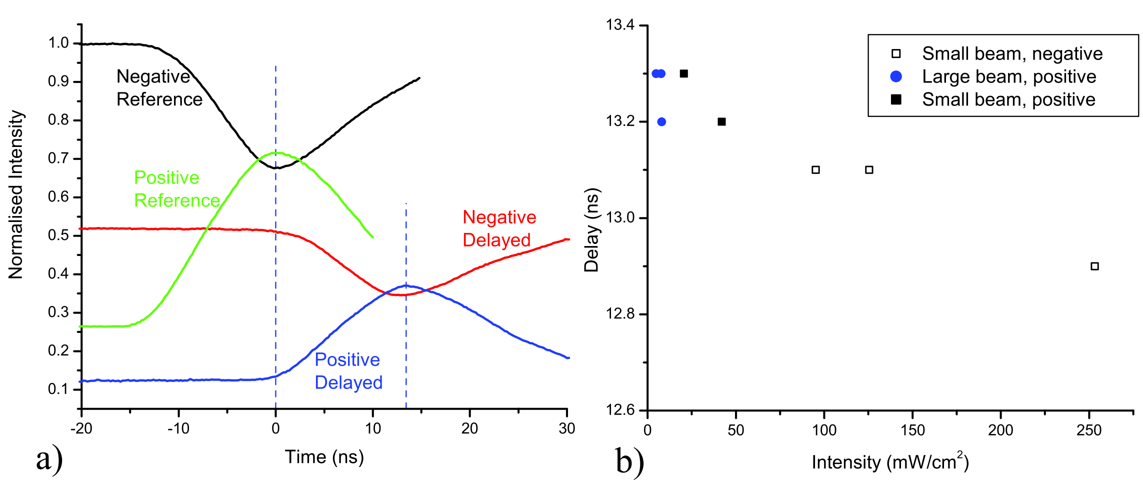

Figure 5. (Colour Online) a) Delay of positive and negative going pulse shapes and b) observations of delay with average intensity of the pulse train at $\sim$ 115°C, where the small and large beam diameters used were 1 and 3 mm, respectively.

(figure 4a). The delay reconfiguration time is mainly limited by atomic time of flight, which is expected to be of the order of microseconds. A range of delay tuning greater than the pulse duration should be possible with shorter pulses.

Measurements of the delay of optical pulses with very low intensity have previously been performed with an average of less than one photon per pulse [14]. In this work however, we are interested in establishing high intensity limits, which we do by using both positive and negative pulse shapes (figure 5a). A negative pulse shape is an interval of reduced intensity on a relatively large optical DC background. Negative pulse shapes are found to exhibit similar delay to positive pulses of comparable intensity, and they may be useful for other applications in that the signal to noise ratio can be higher. Furthermore, such pulses may be of interest in experiments involving atomic or optical coherence. By neutral density filtering and adjusting the beam waist, the delay was measured for a range of values of the intensity of the 10 MHz pulse train (figure 5b). It is observed that the delay decreases with increasing intensity by approximately 1.8 ps/(mW/cm^2). We attribute this to the increase in saturation of the atomic medium, which has the effect of reducing the dispersion.

In conclusion, optical pulses of 9.3 ns duration (FWHM) with frequency tuned between the ^{85}Rb (F=2) and ^{87}Rb (F=1) components of the D_2 line were delayed in a 10 cm vapour cell at 135°C with low distortion by more than 40 ns (fractional delay 4.3) and with approximately 10% transmission. The delay arises from the intrinsic positive dispersion between the two absorption peaks. In this experiment the fractional delay was limited by the pulse duration, but should be ultimately limited by the $\sim$1 GHz transmission window, making a fractional delay of 40 possible.

The dependence of delay, transmission and usable bandwidth with temperature and frequency was investigated. With increasing temperature and atomic density the delay increases and the transmission reduces. This trend also applies as the optical frequency is tuned closer to one of the resonances. A reduction in usable bandwidth was measured with increasing temperature. In addition, the delay was found to reduce with increasing intensity. This was observed using negative pulses, which were delayed in a similar manner to positive pulses.

In contrast to EIT-based delay lines this technique provides the large bandwidth necessary for delaying short optical pulses and also operates at both low and high intensity levels.

Using the spectral region between absorption components of different isotopes for an all-optical delay line allows optical pumping with a single laser to modify the interacting population of one absorption component without modifying the other. Rapid tuning of the delay was obtained in this way over a range more than 40% of the unmodified pulse delay at 110°C.

Finally, we note that such broadband delay lines may be used to delay many forms of optical quantum information encoding such as weak coherent pulses or squeezed states.

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